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TITLE: Emergency Responders' "Rules-of-Thumb" for Air Toxics Releases
in Urban Environments

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Emergency Responders' Rules-of-Thumb
for Air Toxics Releases In Urban Environments

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1.0 Introduction.

Although not an everyday phenomenon, releases of hazardous gases and aerosols have occurred in populated urban environments and are potentially threatening to human life. These releases may stem from on-site accidents as in the case of industrial chemical releases, may result during transport of hazardous chemicals as in tanker truck or railroad spills, or may be premeditated as in a chemical or biological agent terrorist attack.

At accident sites, emergency responders are typically responsible for maintaining order, determining safe-zones, and performing rescue and evacuation. In the event of a poisonous cloud release in an urban area, emergency responders need to be cognizant of the rather complicated transport and dispersion processes that occur around building structures in order to make sound decisions.

This report is meant to help emergency responders, managers, and training personnel become familiar with some of the more common patterns of plume transport and dispersion that develop in built-up areas. A two page "rules-of-thumb" depicts common situations that may occur in an urban environment and gives warnings about potentially fatal consequences if the situation is misinterpreted. These "rules" do not tell the emergency responder what to do, they only are meant to warn the emergency responder that sometimes unexpected or counter-intuitive flow phenomenon may occur. 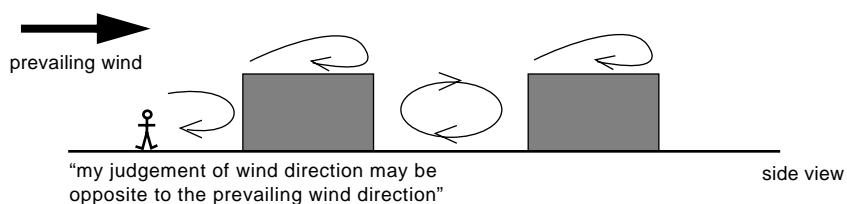The "rules-of-thumb" are meant to give the emergency responder more knowledge so that he or she is better able to avoid fatal errors. It is our belief that some knowledge, though incomplete, is better than no knowledge.

The second part of this report contains citations to studies that support each of the particular rules. By reading these sections, you will see that the "rules" are generalizations supported by a number of different experimental or modeling studies. However, you will also find evidence that suggests that transport and dispersion around building structures is very complicated and that transport and dispersion patterns may be very different depending on building shape, relative heights, etc. Unfortunately, there is not enough data or information available to adequately make rules for the many situations that might occur in real cities.

It is very important to understand that because of the complexities of urban built-up areas, it is very difficult to generalize rules for plume transport and dispersion that work for every case. These "rules-of-thumb" were developed to give emergency responders a general idea of some of the complexities of transport and dispersion of plumes in built-up areas. However, we fully expect that for particular situations some of these generalized "rules" will not apply. We plan to improve the "rules" as we learn more, but for now, we caution users to be conservative in applying "go"-"no-go" decisions based on these rules.

APPARENT WIND ANOMALIES

The locally-measured wind may not match the large-scale wind due to building-induced circulations.

prevailing wind

"my judgement of wind direction may be opposite to the prevailing wind direction"

side view

Lesson: because of the complicated flows that develop around buildings, a measurement of wind made at ground-level may not be indicative of the upper-level prevailing wind. Evacuation zones far downwind must be determined by the larger-scale plume transport which follows the prevailing wind, not the local wind.

AGENT TRAPPING IN VORTICES

For winds nearly face-on to the building wall, concentrations of hazardous material can build-up in between buildings and take a relatively long time to flush out.
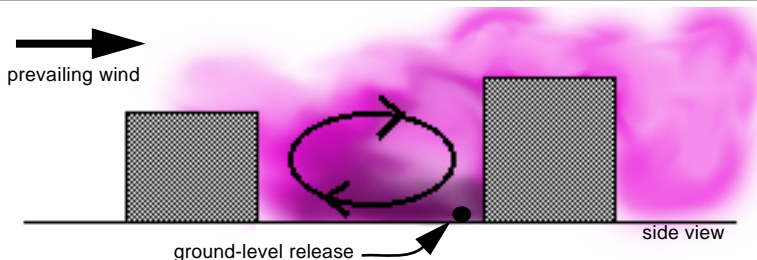
prevailing wind

ground-level release

side view

Lesson: air contaminants can become trapped between buildings in slow moving vortices, thus taking longer to flush out with clean air. In most cases, wider buildings and narrower streets will trap the pollutant longer.

AGENT ENTRAPMENT

Recessed entryways or architectural alcoves may trap and hold air contaminants for some time after the plume has passed by.

current time

later time

prevailing wind

ground-level release

top view
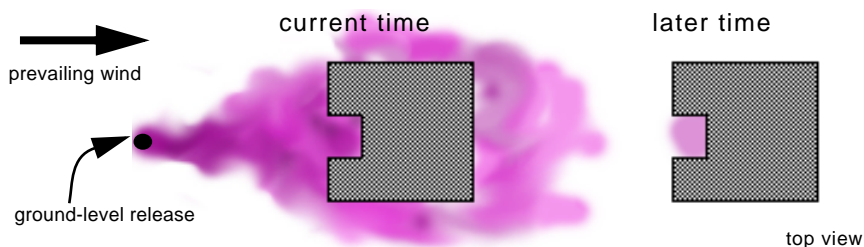
Lesson: even after clearly determining that the main portion of the plume has disappeared, be aware that some of the air contaminant may have collected in alcoves and other zones of stagnation.
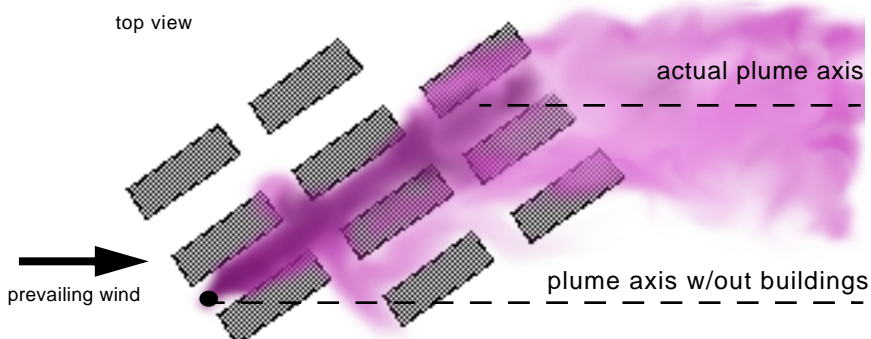
ON-AXIS CHANNELING EFFECTS

For winds parallel to the street, the plume can become contained within the street canyon; however, the plume can travel up side streets.
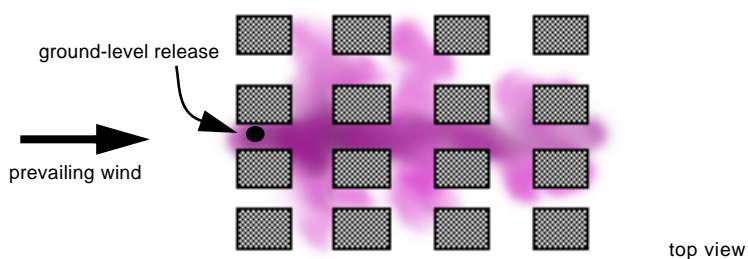
ground-level release

prevailing wind

top view

Lesson: after determining that the prevailing wind direction is parallel to the street containing the release, be aware that contaminated air is likely to travel several blocks in each direction along side streets.
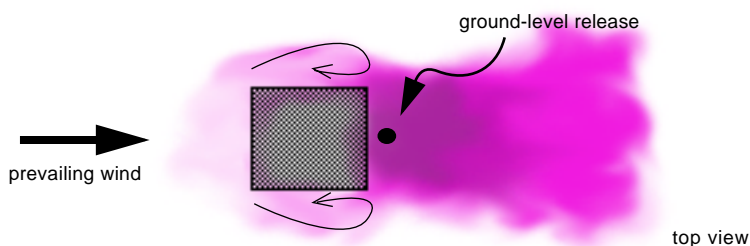
OFF-AXIS CHANNELING EFFECTS

The plume can get channeled by streets near the source and end-up traveling off the prevailing wind direction axis.

top view

actual plume axis

prevailing wind

plume axis w/out buildings

Lesson: for determining larger-scale evacuation zones, be aware that the plume initially may be transported in a direction off-angle from the prevailing wind. Once the plume gets dispersed above the buildings, it will then travel with the prevailing wind, but the plume's center axis will be offset from the release point.

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EDDY TRANSPORT OF AGENT

The air contaminant can move short distances against the prevailing wind direction in recirculation zones along the sides and top of the building.

ground-level release

prevailing wind

top view

Lesson: even if the source is determined to be downwind of you, be careful at locations near the building upstream of the source, as the plume can travel short distances in the opposite direction to the prevailing wind.

LARGE-SCALE WIND VARIABILITY

The prevailing wind switches direction occasionally, so that the upwind safe zone may now be downwind.

current time

later time

prevailing wind

prevailing wind

side view
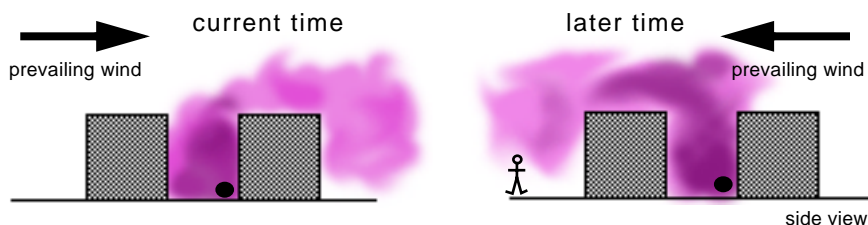
Lesson: the prevailing wind is not fixed and under some circumstances can change direction quickly; thus, monitor the prevailing wind direction so that safe zones can be maintained.

SMALL-SCALE WIND VARIABILITY

The local wind can switch direction very rapidly, so that the plume may switch from one side of the building to the other in a matter of seconds.

prevailing wind

current time

a few seconds later

top view

"I'm safe over here"

"uh-oh"
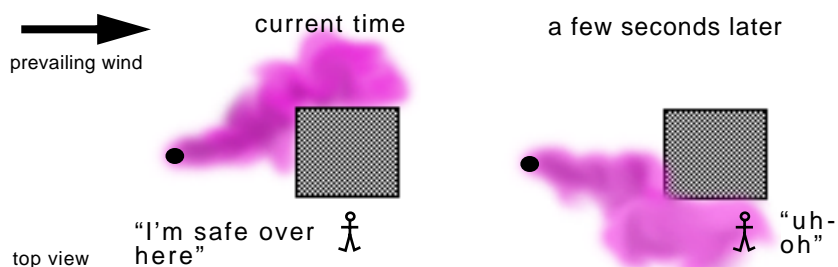
Lesson: due to the turbulent nature of the wind, it is very common for a plume to bounce from one side of the building to the other; hence, don't assume that you are safe on one side of the building just because the plume is currently on the other side.

AGENT DEPOSITION

After the plume has left the area of release, the ground and building surfaces may still be contaminated due to deposition of the toxic agent.

deposition contours
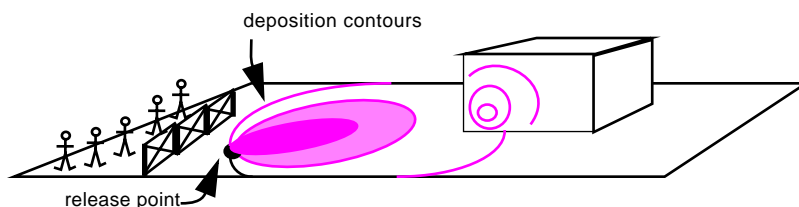
release point

Lesson: because the contaminant may stick to surfaces, touching surfaces in the vicinity of the release point is not recommended until decontamination is complete.

INDOOR EFFECTS

When the plume is passing over, it is probably safer to remain indoors. After the plume has passed by, it may be safer to move outdoors.

current time

later time

safer inside
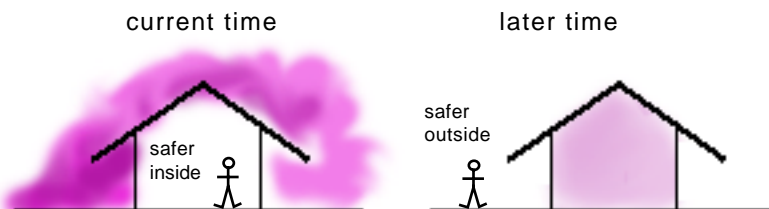
safer outside

Lesson: for an outdoor release, modeling studies show that concentrations can initially be lower indoors, but then later the concentrations become lower outside. These relationships, however, depend upon the details of the building ventilation.

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APPARENT WIND ANOMALIES
The locally-measured wind may not match the large-scale wind due to building-induced circulations.

prevailing wind

"my judgement of wind direction may be opposite to the prevailing wind direction"

side view
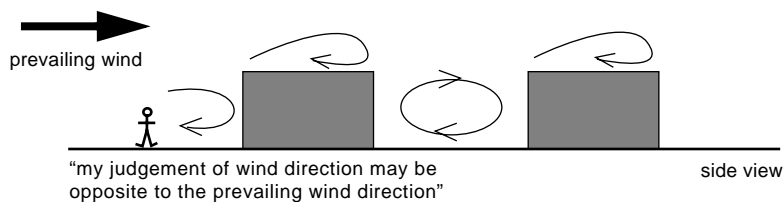
Lesson: because of the complicated flows that develop around buildings, a measurement of wind made at ground-level may not be indicative of the upper-level prevailing wind. Evacuation zones far downwind must be determined by the larger-scale plume transport which follows the prevailing wind, not the local wind.

2.1 Apparent Wind Anomalies

2.1.a) Implications

In most cases, a wind direction measurement taken in between or near buildings should not be used to determine the large-scale transport of the toxic plume. Instead, a wind measurement taken above the building tops or in a region where the flow is not influenced by buildings, trees, or other obstacles should be used to determine the long distance transport of the plume.

Due to the recirculations that form on the top, sides, front-face, and in-between buildings, a wind direction measurement taken within the building canopy may not be representative of the larger-scale regional flow. The wrong neighborhoods could be evacuated if emergency personnel used a wind measurement made within the building canopy to determine the "downstream" direction. Although the measured wind within the building canopy will help with determining the transport of the toxic agent within a block or two of the release, the transport direction of the plume over distances of miles will be primarily determined by the regional-scale wind above the building rooftops.

2.1.b) Evidence/Documentation

Literally hundreds of wind-tunnel experiments documenting the complex flow patterns that develop around buildings have been performed (see review by Hosker,

1984). As shown in fig. 2.1.1, the mean flow field that develops around a 3-d building in a boundary-layer flow contains recirculation zones on the rooftop, building front, building-sides, and in the downstream cavity region (e.g., Hunt et al., 1978). These are ensemble or time average flow features, thus instantaneously the flow field may look different. The length and size of these recirculation regions are dependent on building height, width, downwind length, wind angle, ambient turbulence levels, and perhaps atmospheric stability. For example, the wind-tunnel experiments of Snyder and Lawson (1996) show that the downstream length of the cavity increases for wider buildings, the cavity height decreases for longer buildings, and rooftop reverse flow was found for all cases.
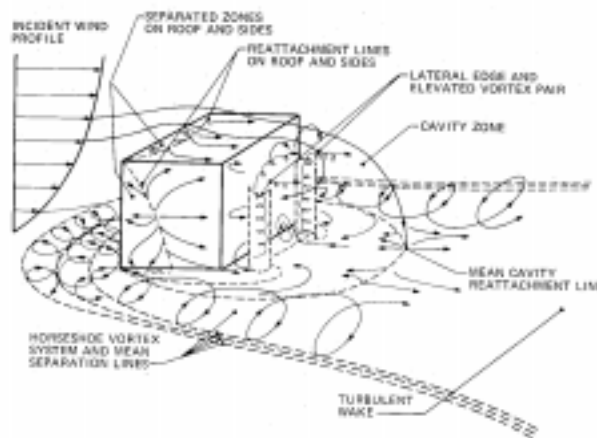

Figure 2.1.1. Flow patterns over a 3-d cube in a turbulent boundary layer based on wind-tunnel experiments. Notice rooftop, sidewall, and cavity recirculation zones [from Hosker, 1984].
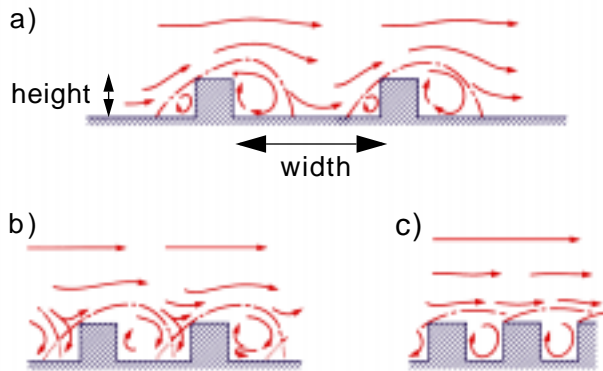
4

a)

height

width

b)   c)

Figure 2.1.2. Flow regimes as function of
width-to-height ratio: a) isolated roughness
flow (w/h > 3); b) wake interference flow
(w/h ≅ 1.5; c) skimming flow (w/h < 1)
[from Oke, 1987].

ROOF VORTEX PLUS CORNER VORTEX

Figure 2.1.3. Illustration of vertically-ori-
ented corner vortex seen in flow visualization
experiments performed by Hoydysh, Griffiths,
and Ogawa (1974) (figure from Hosker,
1987).

There have also been many wind-tunnel
experiments of flow around *two* buildings,
often called urban canyons (e.g., Hosker,
1987). In general, the nature of the flow
between the two buildings is determined by
the ratio of the width between buildings (w)
to the building height (h). There is also a
weak dependence on the cross-sectional
length of the buildings. As summarized by
Oke (1987), a single vortex develops
between buildings for skimming flow (w/h <
1), two counter-rotating vortices may
develop for wake interference flow (w/h ~
1.5), and for isolated roughness flow (w/h
> 3) the flow field looks similar to the single
building case (see fig. 2.1.2).   These
expected flow patterns can be disrupted,
however, by the presence of a tall building.

Hosker (1987) reports that several studies
indicate that a helical vortex will form
between the two buildings if the wind is
within 60 degrees of perpendicular to the
building face, otherwise no vortex forms.
Several wind-tunnel studies by Hoydysh and
Dabberdt (1988) and Theurer et al. (1992)
show that building height differences can
significantly change the urban canyon flow
field.   In addition, peaked roofs and non-
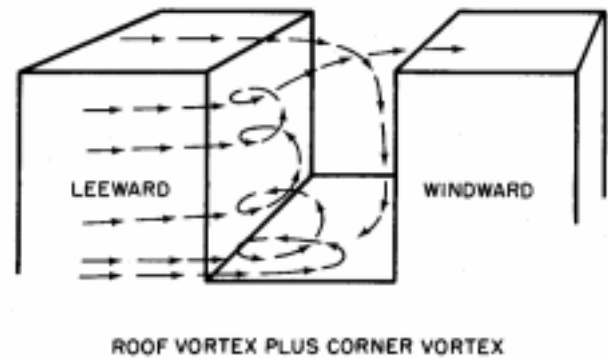rectilinear buildings can alter urban canyon

circulation, but results are currently not
generalizable.

For building clusters, wind-tunnel experi-
ments by Hoydysh and Dabberdt (1988)
show intermittent upward spiraling vortices
at intersection corners for tightly spaced
buildings (see fig. 2.1.3). Based on smoke
visualization studies, Meroney et al. (1996)
found that rooftop recirculation zones do
not form on a series of buildings of equal
height, except for the one furthest
upstream.

The impact of atmospheric stability and
local heating and cooling due to building
surfaces on the flow field around buildings is
not well understood. Numerical modeling
studies by Sini et al. (1996), Kim and Baik
(1998), and Smith and Reisner (1999) sug-
gest that heating of building surfaces and
ambient atmospheric stability can signifi-
cantly alter the flow patterns in the urban
canyon. For example, Sini et al. (1996)
found that when the downstream canyon
wall was heated two vortices developed
rather than one. These effects, however,
have not been validated in real-world exper-
iments.

AGENT TRAPPING IN VORTICES
For winds nearly face-on to the building wall, concentrations of hazardous material can build-up between buildings and take a relatively long time to flush out.
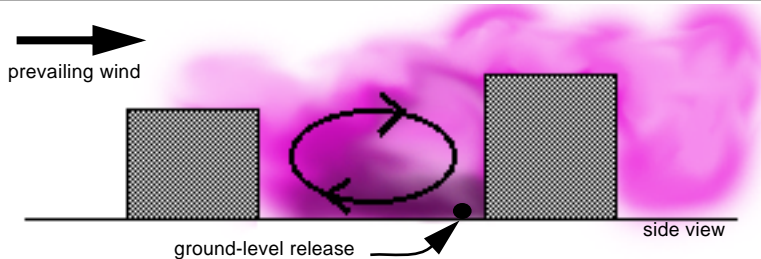
prevailing wind

ground-level release

side view

Lesson: air contaminants can become trapped between buildings in slow moving vortices, thus taking longer to flush out with clean air. In most cases, wider buildings with relatively narrower streets will trap the pollutant longer.

2.2 Agent Trapping in Vortices

2.2.a) Implications

Even with strong prevailing winds, the concentration levels of a contaminant released between two buildings can remain high for an appreciable amount of time if the prevailing wind direction is not parallel to the street canyon. For this case, one, two, maybe even three weakly rotating vortices can form between the two buildings and act to trap the pollutant between the buildings in the street canyon. When the prevailing wind is nearly face on to the building walls, the wind speed in the street canyon is generally small (on the otherhand, significant speed up and hence contaminant dilution can occur when the wind runs along the street).

Traditional dispersion models (e.g., Gaussian puff) that use the prevailing wind speed would underestimate the time necessary for dilution of the plume to safe levels. For a toxic agent release between buildings, it is, unfortunately, very difficult to estimate the dilution time since it is a function of building spacing, heights, relative heights, width, shape, wind angle, source strength and possibly stability conditions. Nonetheless, a few empirical expressions are given in the next section.

2.2.b) Evidence/Documentation

A few field experiments have been performed that show pollutant trapping in urban canyons (e.g., DePaul and Shieh, 1985; Qin and Kot, 1993). Many more wind-tunnel experiments have been performed to study the dispersion of contaminant releases between two buildings (see reviews by Hosker, 1987 and Yamartino et al., 1989). For buildings of similar height with flat roofs, the nature of the flow between the two buildings is a function of the ratio of the width between buildings (w) to the building height (h). There is also a weak dependence on the cross-sectional length of the buildings. As summarized by Oke (1987), a single vortex develops between buildings for skimming flow (w/h < 1), two counter-rotating vortices may develop for wake interference flow (w/h ~ 1.5), and for isolated roughness flow (w/h > 3) the flow field looks similar to the single building case (see fig. 2.1.2).

When the buildings are spaced closer together (w/h < 3) and the mean flow direction is within ± 60 degrees of being perpendicular to the building faces (e.g., Dabberdt et al., 1973), the flow between the buildings can become disconnected from the upper-level prevailing flow, that is, the flow above the buildings does not penetrate down between the buildings. The weakly rotating vortices that develop between the buildings can trap air contaminants released at street level (e.g., fig. 2.2.1).

Several simple dilution expressions have been derived from wind-tunnel and numerical experiments. Lee and Park (1994), for example, found that an exponential decay formula described well the bulk concentra-
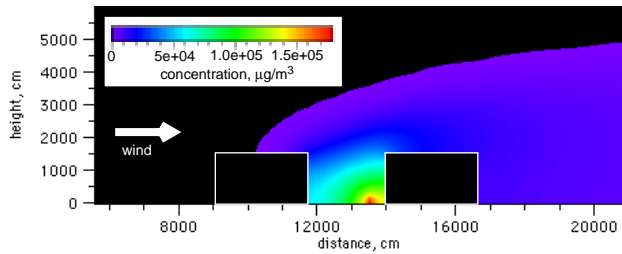
6

Figure 2.2.1. Concentration fields computed for a surface release between two 2-d buildings. Due to reduced ventilation, extremely high concentration values are found in the urban canyon [from Brown and Muller, 1997].

tion in an urban canyon:

$$C_{bulk} = C_{bulk\ max}\ e^{-t/T}$$

where t is time after release and T is the dilution time scale. The dilution timescale T is very large for small w/h (i.e., it takes a long time for dilution of the air contaminant when the spacing between buildings is small) and decreases rapidly as w/h increases (i.e., dilution of the air contaminant increases as the spacing between buildings increases). For wide buildings of equal height, dilution timescales ranged from 1000's of seconds for w/h < 0.5 to 100's of seconds for w/h >1.

Lee et al. (1994) found that the dilution timescale decreased as the wind direction shifted from perpendicular to the street towards larger oblique angles, i.e., the air contaminant flushes out of the canyon slowest when the approach flow wind angle is perpendicular to the street canyon axis. For a 45 degree wind angle, the dilution timescale was reduced by about one-half. Wind-tunnel experiments by Cermak et al. (1974) and Wedding et al. (1978) support the finding that dilution is a function of wind angle.

The dilution time should also be a function of building frontal width, stability, relative building heights, and roof type (e.g., flat vs.

pitched). For example, Hoydysh et al. (1974) found that tall buildings interspersed among shorter buildings resulted in reduced street-level concentrations due to the increased ventilation from spiral vortices induced by the tall buildings. Recent wind-tunnel experiments by Rafailidis and Schatzmann (1995) indicate that pitched roofs can significantly alter the concentrations between buildings, often resulting in increased ventilation in the street canyon.

The dilution approach cited above generally does not account for within canyon variations in the concentration field or intermittent flushing of the contaminant. Dabberdt and Hoydysh (1991) and Meroney et al (1996) found that pollutants trapped in the urban canyon intermittently flush out. Several studies have found significantly higher concentration levels at the upstream side of the canyon as compared to the downstream side for centerline surface level tracer releases and automobile emissions (e.g., Dabberdt and Hoydysh, 1991; Johnson et al., 1973). The opposite condition was found, however, by Hodysh and Dabberdt (1988) when the upstream building was taller, i.e., the upstream side of the canyon had lower concentrations than the downstream side. For buildings of equal height, the single vortex velocity equations derived by Hotchkiss and Harlow (1973) works fairly well and leads to higher concentrations on the upstream side of the canyon. A number of relatively simple analytical or empirical models have been devised to account for plume dispersion within the canyon (e.g., Johnson et al., 1973; Yamartino and Wiegand, 1986; Benson, 1992, Eerens et al., 1993), several of which use the Hotchkiss and Harlow (1973) vortex equations. These codes, in general, account for upstream and downstream in-canyon differences, wall reflections, and ventilation effects as a function of w/h and approach flow wind angle. However, it is probably fair to say that they are limited in their use to relatively simple building configurations and shapes.

AGENT ENTRAPMENT
Recessed entryways or architectural alcoves may trap and hold air contaminants for some time after the plume has passed by.

prevailing wind

current time

later time

ground-level release

top view
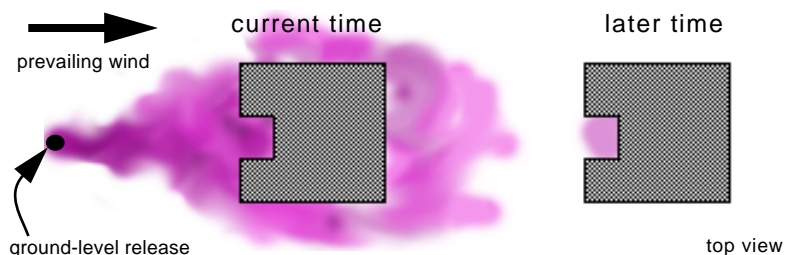
Lesson: even after clearly determining that the main portion of the plume has disappeared, be aware that some of the air contaminant may have collected in alcoves and other zones of stagnation.

2.3 Agent Entrapment

2.3.a) Implications

In alcoves, many building entrances, unloading areas, beneath overhangs, and in other building nooks, the wind can stagnant or recirculate. It is possible that for some time after the prevailing wind has carried away the main portion of the plume, a dangerous amount of contaminant may still remain in these stagnation zones. If the agent release is dense relative to air, it may collect in low-lying areas as well.

These areas are often places where people congregate, so emergency response personnel should be cognizant of the possibility that the air in these stagnation zones could remain contaminated a relatively long time beyond what a traditional Gaussian puff model would estimate. Because of the varied configurations of building crevices, it would be very difficult to make general statements about the time needed for the air to reach safe levels.

2.3.b) Evidence/Documentation

We are are aware of only a few published reports in the open literature looking at this phenomenon explicitly. However, many wind-tunnel experiments have been performed of scaled-down real-world building configurations, a few of which undoubtedly contain cavity regions in and around the buildings. Reports from private, university,

and/or government run wind tunnels (e.g., Colorado State University, Environmental Science & Services Corporation) may contain information that corroborates the stagnation phenomenon in building depressions.

A wind-tunnel study performed by Leitl et al. (1997) looked at dispersion in and around a U-shaped building. For one case, the source was placed in the alcove at ground-level and the wind was perpendicular to the flat side of the building opposite the alcove. Concentrations were observed to be high near the upstream edge within the alcove, however, detailed measurements within the alcove were not reported. Results from several different fluid dynamics numerical models showed very high concentrations within the alcove and immediately above the alcove and downstream of the building, indicative of the tracer being trapped in the alcove and then lofted by vortices upwards.

In wind-tunnel visualization experiments we performed recently at the USEPA Fluid Modeling Facility, we found that after the source was turned off the plume remained for some time in a vestibule on the downstream side of the building. However, no detailed measurements were taken, nor were other configurations studied.

There are engineering and industrial fluid dynamic studies that might be used as surrogates for understanding trapping in building crevices. For example, slot, cavity, engine, machinery and duct flow studies

often involve flow over cavity regions. Van Dyke (1982) contains several examples of flows that illustrate recirculation and stagnation in cavities. Chen and Jaw (1998) show comparisons of computational fluid dynamics model results with experimental data for turbulent flows past channel cavities, pipe cavities, and rectangular cavities. Both models and experimental results show that vortices develop in the cavity and presumably would result in trapping of pollutants.

ON-AXIS CHANNELING EFFECTS
For winds parallel to the street, the plume can become contained by the street canyon; however, the plume can travel up side streets.
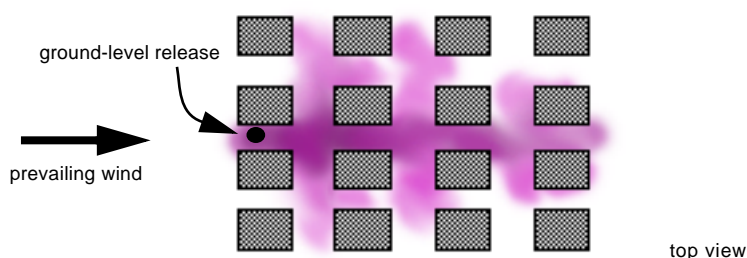
ground-level release

prevailing wind

top view

Lesson: after determining that the prevailing wind direction is parallel to the street containing the release, be aware that contaminated air is likely to travel several blocks in each direction along side streets.

2.4 On-axis Channeling Effects

2.4.a) Implications

Buildings can act like a channel and force the plume to travel down the street. In general, the drag imparted by buildings acts to slow down the wind. If the prevailing wind is parallel to the street canyon, vertical lofting of the air contaminant may not occur and the plume may become trapped below building height.

In some cases, however, a few buildings may channel the flow resulting in relatively high wind speeds. In this case, a toxic agent released within the street channel may flush out rapidly due to the high winds and associated turbulent mixing. Unfortunately, in a complex urban environment, it is difficult to give a rule-of-thumb for when speed-up occurs and when it doesn't.

In addition to the channeling effect, the plume is usually transported up the side streets due to the circulating vortices that develop in the adjacent cross street urban canyons. Hence, the plume may travel up side streets several blocks perpendicular to the prevailing wind direction. Emergency response personnel therefore should not assume that sidestreets are safe zones. Moreover, traditional Gaussian plume models without urban canopy parameterizations may underestimate the lateral spread of the plume.

2.4.b) Evidence/Documentation

As shown in Hosker (1984), experiments by Gandemer (1976) found speed-up factors at pedestrian level of up to 1.3-1.6 for different building configurations that channel the flow. The channelized flow tends to reduce concentrations near the source, as pollutants are carried away rapidly rather than being trapped. However, concentrations may remain relatively high at street-level further downstream due to limited vertical lofting of the channelized plume (e.g., Hoydysh and Dabberdt, 1994).

However, in clusters of regularly-spaced buildings of near-equal height, winds in the street channels have been found to be smaller than the prevailing upstream wind (e.g., Davidson et al., 1996). Hoydysh and Dabberdt (1991) found that concentrations at mid-block were actually highest when the wind was parallel or perpendicular to the street canyon and lowest at intermediate wind angles. Hence, for some cases a prevailing wind parallel to the street canyons may flush out air contaminants quickly due to jetting of the flow and in other cases the plume will dilute more slowly as the winds will travel slowly and the plume will be contained within the street canyon. At this time, it is not possible to determine when one or the other will occur.

Due to circulations that develop on the side streets, some of the air contaminant is transported perpendicular to the mean wind direction. Figure 2.4.1 shows a smoke

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tracer being mixed into the side streets during a wind-tunnel experiment.
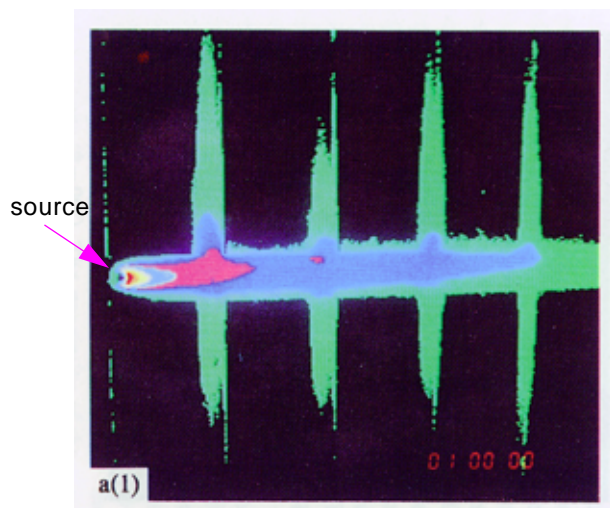
Figure 2.4.1. Wind-tunnel smoke plume visualization viewed looking down on buildings. Release is at street-level and flow is from left to right. Notice the channeling and side street transport of the plume (from Hoydysh and Dabberdt, 1994).

On the larger-scale, the enhanced lateral mixing of the plume (due to increased turbulence levels and sidestreet transport) is implicitly accounted for by Gaussian dispersion models that use urban σ_y curves (the curves were derived from urban field experiments and thus are larger than the corresponding rural σ_y curves) (e.g., Turner, 1994; Boubel et al., 1994). However, they have no dependence on building height-to-width ratios, relative building heights, or approach flow angle and do not explicitly account for mixing within the urban canopy.

OFF-AXIS CHANNELING EFFECTS
The plume may be confined and channeled by buildings near the source so that it travels off-angle to the prevailing wind direction.
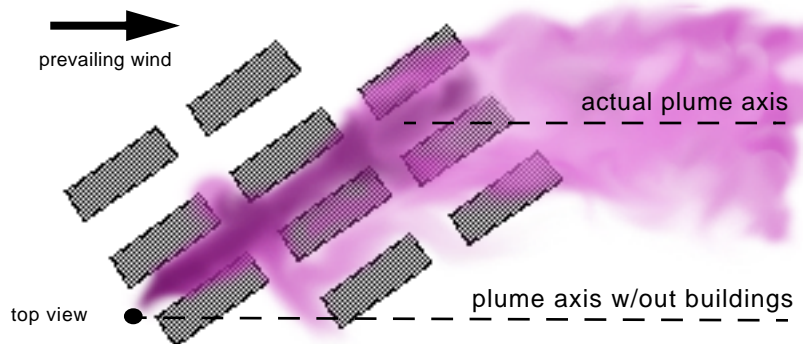
prevailing wind

actual plume axis

top view

plume axis w/out buildings

Lesson: for determining larger-scale evacuation zones, be aware that the plume initially may be transported in a direction off-angle from the prevailing wind. Once the plume gets dispersed above the buildings, it will then travel with the prevailing wind, but the plume's center axis will be offset from the release point.

2.5 Off-axis Channeling Effects

2.5.a) Implications

Since a group of buildings can channel the flow at street level, a plume released in the street below the building tops can travel for several blocks in a direction oblique to the prevailing wind direction. Only when the plume gets dispersed above the building tops will a portion of the plume travel in the direction of the prevailing wind.

Emergency response personnel should be aware that it may be wrong to assume that only the region directly downwind from the source should be evacuated when the wind is not blowing parallel to the street canyons. Due to the channeling of the flow at street level, one should consider that the small-scale transport of the plume will generally follow the street, while the larger-scale transport of the plume will usually be parallel but displaced from the line defined by the source and the prevailing wind direction. Hence, using winds reported by the National Weather Service or from the local airport may not be indicative of what is happening within a cluster of buildings. Moreover, the lateral spread of the plume at large downwind distances may be significantly larger than predicted by a Gaussian dispersion model since the channeling of the plume at street level extends the crosswind transport of the plume. Several research groups have proposed modifications to the Gaussian plume model to account for the off-axis plume transport; we will discuss these below.

2.5.b) Evidence/Documentation

Wind-tunnel experiments by Hoydysh and Dabberdt (1994) and Theurer et al. (1996) demonstrate that plumes can become trapped in street canyons and travel in an oblique direction to the large-scale prevailing wind. Figure 2.5.1 shows the bulk of the plume being channeled down the street
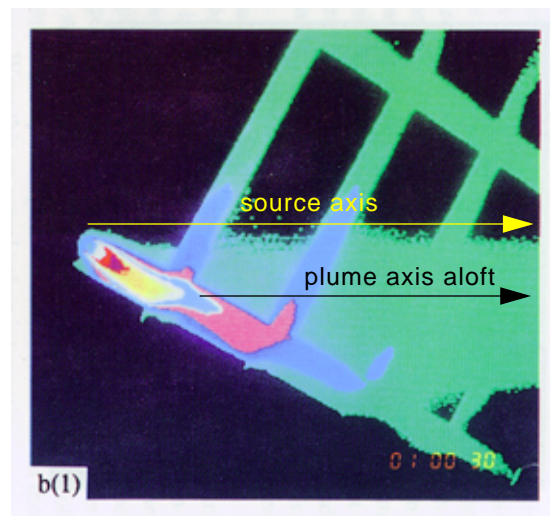

source axis

plume axis aloft

b(1)

Figure 2.5.1. Wind-tunnel smoke plume visualization viewed looking down on buildings. Release is at street-level and flow is from left to right. Notice that channeling causes the plume to travel at an oblique angle to the prevailing wind direction (from Hoydysh and Dabberdt, 1994).

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with one fraction of it going up side streets and another fraction of it being lofted above roof-level and traveling with the prevailing wind. Notice that the centerline plume axis is shifted from the source axis.

Theurer et al. (1996) performed a large number of experiments in order to determine the impact of different building configurations and prevailing wind directions on the plume axis shift and spread. They found that plume axis shift was strongly dependent on wind angle with 0 and 90 degree approach flows giving a minimum impact and a 45 degree approach flow giving the maximum impact (the 30 and 60 degree results were not shown). In addition, wider buildings had a slightly greater impact on the plume axis shift than narrow buildings. They also found that a Gaussian plume model with modified plume spread parameters and a virtual source offset from the real source describes the plume fairly well once the plume gets above the rooftops. Unfortunately, not enough information is given in the Theurer et al. (1996) paper to reconstruct their Gaussian plume model that accounts for building cluster effects.

EDDY TRANSPORT OF AGENT
The air contaminant can move short distances against the prevailing wind direction in recirculation zones along the sides and top of the building

ground-level release

prevailing wind

top view
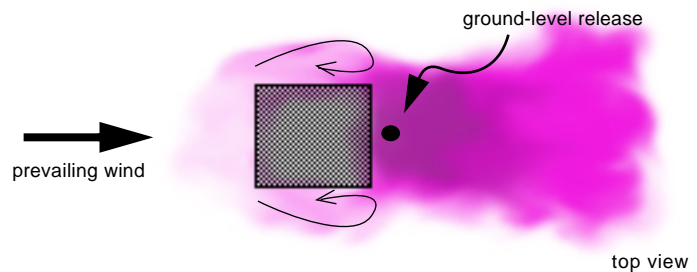
Lesson: even if the source is determined to be downwind of you, be careful at locations near the building upstream of the source, as the plume can travel short distances in the opposite direction to the prevailing wind.

2.6 Eddy Transport of Agent

2.6.a) Implications

Even with a steady prevailing wind, intermittently forming vortices, or rotational winds, that develop on the building sidewalls and rooftop can transport air pollutants in a direction opposite of the prevailing wind direction. Enhanced turbulent mixing directly downstream of the building can loft air contaminants from a ground-level source to the rooftop where they can then be entrained into the rooftop recirculation zone.

Although these rooftop and sidewall circulations are not persistent, intermittent bursts of contaminants can be advected upstream against the prevailing wind. Emergency response personnel should be aware that an upwind position may not be safe even when the prevailing wind is persistent. In addition, these intermittent bursts often contain undiluted contaminant agent; therefore, instantaneous dosages to exposed people may be very high.

2.6.b) Evidence/Documentation

Many wind-tunnel experiments have been performed that show a recirculation region along the sidewalls and rooftop of a single building (e.g., Castro and Robins, 1977; Hosker, 1984; Martinuzzi and Tropea, 1993). Although these may be intermittent in nature, they do on average transport material upstream. For example, fig.
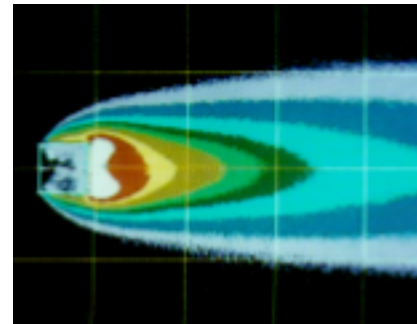

Figure 2.6.1. Wind-tunnel experiment showing vertically-integrated concentration contours for a surface release on the downstream (right) side of the building [from Lee et al., 1991]. Notice that the tracer has moved upstream along the sidewalls and rooftop.

2.6.1 shows time-averaged vertically-integrated concentration contours for a source at ground-level on the downstream side of a cube. There are significant concentration levels found adjacent to the building sidewalls, as well as low concentrations on the cube top. For an outdoor rooftop release, Oikawa and Meng (1997) found that significant quantities of pollutant were transported upstream in the rooftop recirculation vortex.

When the approach flow is not perpendicular to the building face, the sidewall recirculations may extend and merge with the downstream cavity behind the building (e.g., Hosker, 1984). Hansen and Cermak (1975) found that the rooftop recirculation is destroyed or reduced by a counterrotating vortex pair for approach flow wind angles between 37 and 57 degrees. How-

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ever, the counterrotating vortices will still act to transport contaminants upstream.

There has been little study of the impact of the atmospheric stratification on the nature of the recirculation zones. Several studies reviewed by Hosker (1984) indicate that ambient turbulence influences the size and strength of the rooftop and sidewall recirculation zones. Since atmospheric stability affects the ambient turbulence levels, it would seem reasonable that stability would alter the building recirculation zones. Wind-tunnel work by Yang and Meroney (1970) indicates that the height of the wake behind an isolated building is smaller for stably stratified flow typical of nighttime conditions, thus increasing ground-level concentrations in the wake. Although field experiments by Higson et al. (1995) did not directly measure the recirculation zones, their concentration measurements upstream and downstream of a single building indicated significant differences in the real-time behavior of the plume for stable and unstable conditions.

Whether the same or similar circulation patterns are found for buildings in the midst of other buildings is debatable and probably depends on the relative heights, spacing, and specific geometries of the buildings. Due to the impact of the other buildings on the approach flow, separation of the flow streamlines at the upstream edges of a building may not occur and therefore the recirculation vortices will not develop on the sidewalls and rooftop. For example, Meroney et al. (1996) found that rooftop recirculation zones did not form on a series of buildings of equal height, except for the one furthest upstream. However, wind-tunnel experiments by Hoydysh and Dabberdt (1988) show intermittent upward spiraling vortices at intersection corners for tightly spaced buildings that can transport air contaminants upward and perhaps a little upstream.

The snapshots of plume dispersion around
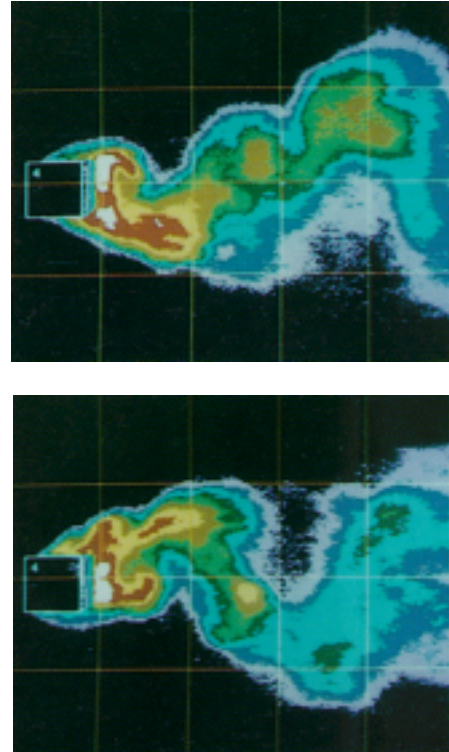
Figure 2.6.2. Wind-tunnel experiment showing instantaneous plume dispersion in the vicinity of a building [from Lee et al., 1991]. The time-averaged picture is shown in fig. 2.6.1.

single buildings by Lee et al. (1991) show that instantaneously the concentrations within the plume can be very high. Traditional dispersion models that compute time-averaged concentrations may severely underestimate the peak human dosages.

LARGE-SCALE WIND VARIABILITY
The prevailing wind switches direction occasionally, so that the upwind safe zone may now be downwind

current time

prevailing wind

later time

prevailing wind

side view
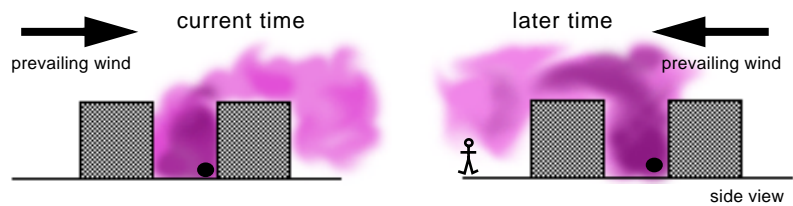
Lesson: the prevailing wind is not fixed and under some circumstances can change direction quickly; thus, monitor the prevailing wind direction so that safe zones can be maintained.

2.7 Large-scale Wind Variability

2.7.a) Implications

The prevailing wind can switch direction on the order of minutes to hours. These directional shifts occur, for example, as a result of changing large-scale weather conditions, the onset of mountain slope, valley drainage and seabreeze flows, and the change of air stability due to heating or cooling of the earth's surface.

For maintaining safe zones, emergency response personnel should continuously monitor the prevailing wind direction. They should be extra cautious during periods of transition, e.g., sunrise/sunset and the passage of weather fronts. They should also be aware that the prevailing wind can change with height and location, so that safe zones based on dispersion models using a single prevailing wind as input may be incorrectly predicted far from the source, e.g., as the plume gets lofted higher into the atmosphere the wind there may carry it in a different direction than the lower elevation wind.

2.7.b) Evidence/Documentation

Large-scale, i.e., synoptic or mesoscale, wind variability has been well documented. Most of us are familiar with synoptic scale weather, such as the passage of cold or warm weather fronts, from newspaper or television reports. Fronts are abrupt boundaries between two different air masses having different thermal and hydro-dynamic properties. Fronts are associated with low pressure systems and the winds blow cyclonically around the low. At the interface between the different air masses (on the order of 100 km wide), the winds usually shift direction abruptly (see fig. 2.7.1). Fronts may move on the order of 1000 km per day.
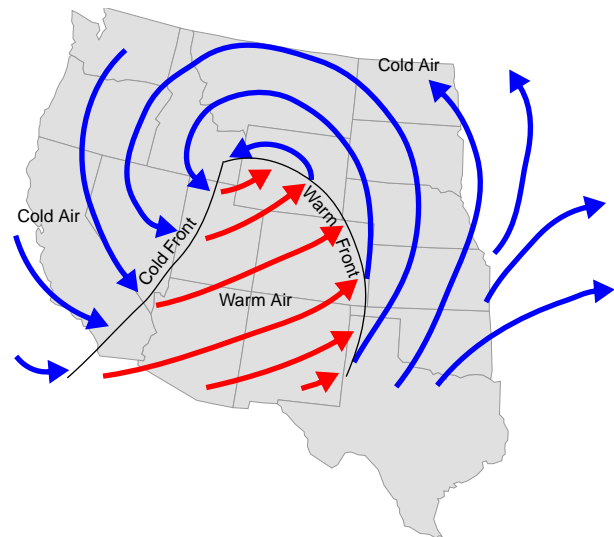

Figure 2.7.1. Idealized synoptic-scale weather system depicting the warm and cold fronts and the associated surface streamlines [adapted from Neiburger et al., 1982].

Thunderstorms and mesoscale convective complexes (large, long-lived groups of thunderstorms) can locally cause wind variability over scales of kilometers. Thunderstorms are associated with periods of gustiness, downdrafts and updrafts. As fig. 2.7.2 shows, there may be a sudden shift in wind direction at the leading edge of a convec-

9 km

TROPOSPHERE

-40°C

0°C

SQUALL FRONT

updraft
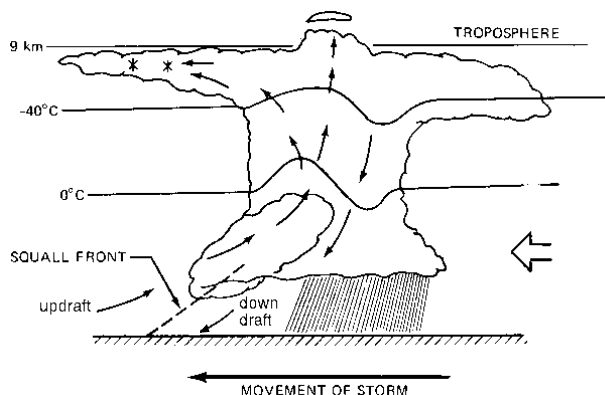
down draft

MOVEMENT OF STORM

Figure 2.7.2. Idealized cross-sectional view of mature thunderstorm showing updrafts, downdrafts, and wind direction shift at leading edge of thunderstorm [from Pendergast, 1984].

tive cloud system.

Mountains, valleys, land-sea interfaces, and other variations in surface characteristics can cause large-scale wind variability as well. These mesoscale weather patterns produced by topographical features 10 to 1000 km in size include mountain upslope and down-slope flows, valley drainage winds, sea-breeze flows, and urban heat island circulation (e.g., Pielke, 1984; Oke, 1987). The winds produced by these mesoscale features are generally driven by heating and cooling differences of the underlying surfaces and result in time-varying wind patterns. For example, winds may shift direction sometime after sunrise for cities located near mountainous terrain as the mountains heat up, the heated air rises, and then pulls surrounding air up the mountain slopes. After sunset the winds may blow in the opposite direction as the mountains cool, the heavy air sinks pulling surrounding air down the mountain slopes (e.g., Williams et al., 1995, Kunz and Moussopolis, 1995).

Cities located near large bodies of water can be influenced by seabreezes or lake breezes (e.g., Simpson, 1997; Lyons et al.,

1995). During the daytime, the land heats up more than the water body as a result of the higher heat capacity of water. The warmer air rises over the land, sinks over the water, and mass conservation requires that the air near the surface blows from the water towards the land and at high elevations in the opposite direction. During the nighttime, a landbreeze circulation in the opposite direction forms with air blowing from the land towards the water near the surface.

Cities themselves typically have different thermal properties than the surrounding rural areas. At nighttime, it is typical for a city to be several degrees warmer than the surrounding area (e.g., Oke, 1987). The warm air above the city rises, pulling in surrounding air. Hence, sometime after sunset, the winds may change direction and flow radially inwards towards the city center (Bornstein, 1987).

It should be emphasized that usually several synoptic and mesoscale phenomenon occur simultaneously in a city and therefore it becomes difficult to predict when and where the large-scale wind direction variations occur and the magnitude of the changes.

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SMALL-SCALE WIND VARIABILITY
The local wind can switch direction very rapidly, so that the plume may switch from one side of the building to the other in a matter of seconds

prevailing wind · current time · a few seconds later

"I'm safe over here" · top view · "uh-oh"
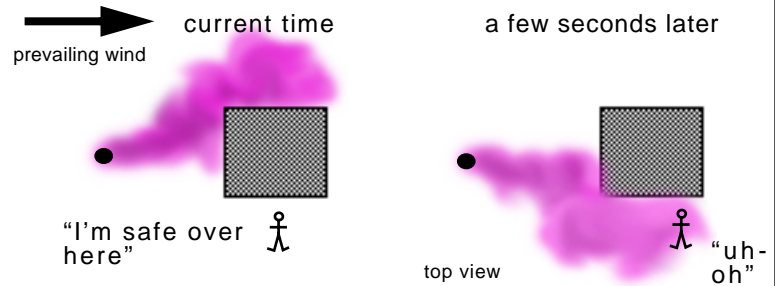
Lesson: due to the turbulent nature of the wind, it is very common for a plume to bounce from one side of the building to the other; hence, don't assume that you are safe on one side of the building just because the plume is currently on the other side.

2.8 Small-scale Wind Variability

2.8a) Implications

The prevailing wind is hardly ever completely steady, but instead shifts its direction and speed rapidly on the order of seconds. On average the wind may blow in a preferred direction, but instantaneously the wind may be pointing in a somewhat different direction. For low prevailing wind speeds, the wind may completely reverse direction in a matter of seconds.

This means that even when a toxic plume is visible and determined to be blowing in a different direction, one should get completely upstream of the plume (see Section 2.6 which warns that vortices that develop on the sides of buildings can transport the plume upstream against the prevailing wind). For low wind conditions or for sunny warm days, one should even be more cautious as the turbulent nature of the wind may nearly instantaneously cause the plume to reverse its travel direction. Below, we discuss some typical ranges in the variability of the wind as a function of meteorological conditions.

2.8.b) Evidence/Documentation

Winds blowing over the earth's surface are naturally variable or turbulent. Figure 2.8.1 shows wind direction measurements made at nighttime over a relatively flat surface. In another study, Peterson and Lamb (1992)
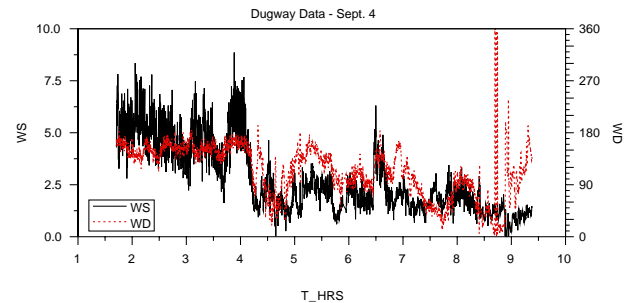

Figure 2.8.1. Wind speed and direction measurements from Dugway Proving Grounds, Utah that show the natural variability in the wind.

found that the wind direction standard deviation σ_θ, a measure of the variability of the wind, is larger for unstable (typically daytime) conditions and smaller for stable (typically nighttime) conditions. These measurements were made in rolling wheat fields, however, not in an urban environment. In table 2.8.1, we show the values reported by Zannetti (1990) for σ_θ as a function of Pasquill-Gifford stability class.

Table 2.8.1 σ_θ as function of stability

stability class	σ_θ range (degrees)	stability definition
A	> 22.5	daytime, calm winds, strong insolation
B	17.5-22.5	daytime, light winds, moderate insolation
C	12.5-17.5	daytime, med. winds, slight insolation

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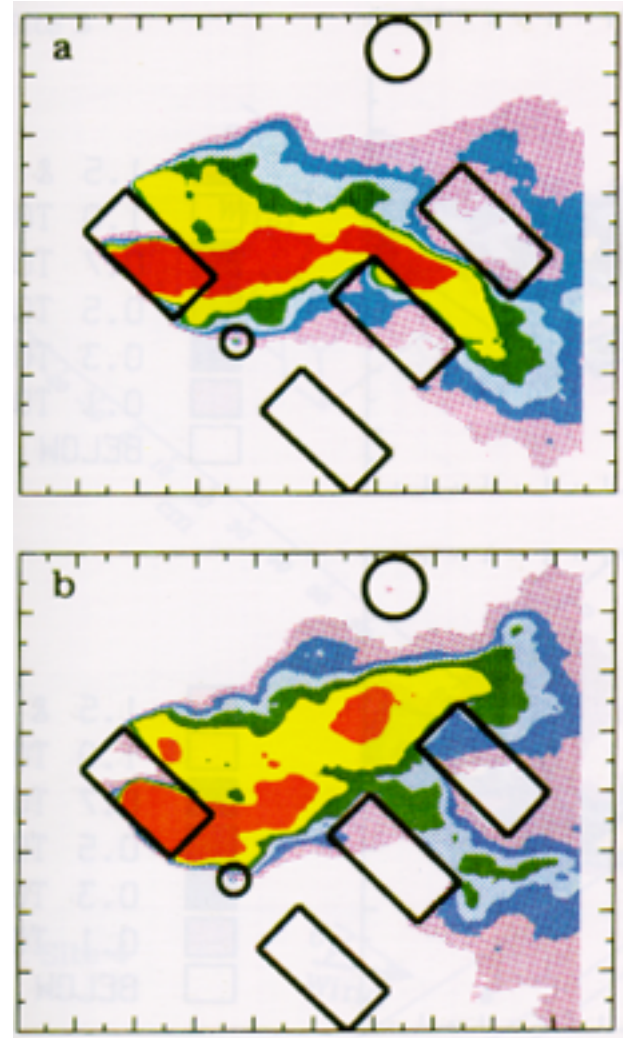| stability class	σ_θ range (degrees)	stability definition
D	7.5-12.5	1) daytime, strong winds, slight insolation or 2) nighttime, med. to strong winds, light overcast or 3) day or night, overcast
E	3.8-7.5	nighttime, med. winds, thin overcast
F	< 3.8	nighttime, calm winds, few clouds

Figure 2.8.2. Instantaneous snapshots of dispersion around buildings showing plume meander. Wind-tunnel measurements are vertically-integrated [from Lee and Hoard, 1992].

The values in Table 2.8.1, however, are for rural terrain. Wind direction fluctuations may be larger than shown above due to building-induced turbulence. Moreover, stability classes A and F may not exist in urban areas due to the moderating influence of the urban canopy.

A number of wind-tunnel and field experiments of plume releases upstream of buildings have been performed that show the plumes chaotically fluctuating around the building (e.g., Higson et al., 1995). The sequential snapshots in figure 2.8.2 show the plume centerline of a vertically-integrated plume moving from one side of a building to the other. The buildings themselves create swirling motions that intermittently appear and dissappear (e.g., Li and Meroney, 1983). Hence, the wind may be intermittently calm and chaotic at street level. Wind direction measurements may for short time periods show very little fluctuation and then suddenly rapidly vary as a burst of swirling air is brought down to street level.

One important consequence of the small-scale wind variability is that "blobs" of nearly undiluted contaminant are transported intact by the turbulent eddies (as shown in fig. 2.8.2). In a brief instant, persons may be exposed to extremely high dosages. The peak concentrations that people are exposed to may be much higher than predicted by traditional plume dispersion models that compute time-averaged quantities.

AGENT DEPOSITION
After the plume has left the area of release, the ground and building surfaces may still be contaminated due to deposition of the toxic agent

deposition contours
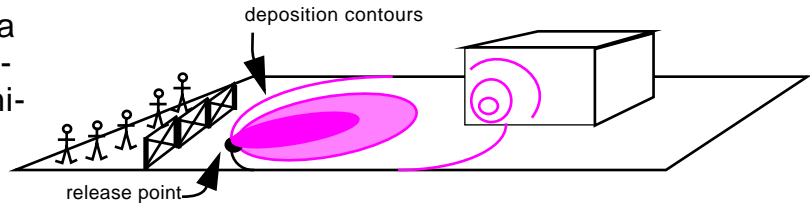
release point

Lesson: because the contaminant may stick to surfaces, touching surfaces in the vicinity of the release point is not recommended until decontamination is complete.

2.9 Agent Deposition

2.9.a) Implications

Depending on the chemical properties of the agent, the surface type, and the meteorological conditions, a fraction of the gaseous or aerosol plume will deposit onto the ground and building surfaces. The deposited material may be invisible to the naked eye, but emergency response personnel should treat areas over which the plume passed as potentially contaminated. Moreover, aerosol agents can be reentrained into the air during wind gusts, so that breathing apparatus may still be needed downwind of the contaminated zone.

2.9.b) Evidence/Documentation

Quantification of the amount of material deposited on the ground from aerosol and gaseous dispersion is very uncertain due to unreliable experimental measurements and difficulty in modeling from first principles. Deposition velocity, defined as the ratio of mass flux onto the surface (kg m^{-2} s^{-1}) to mean concentration (kg/m^3) at some specified height, is frequently used to compute plume depletion (Pasquill and Smith, 1983). Experimentally-determined deposition velocities (e.g., Sehmel, 1984), however, show values spanning 5 orders of magnitude and for a specific gas or particle species the range usually covers 1 to 2 orders of magnitude. Much of the variation is due to differences in meteorological and underlying surface conditions, uncertainty in initial particle size distributions, and the inherent limitations of experimental methods.

Experimental measurements performed in the 1960's and 70's with uranine particles can give an approximation for how rapidly the plume might be depleted for an aerosol release. These field experiments show from 10 to 50% of the particles deposit on the ground in the first 200-400 meters from the source and from 40-95% of the particles deposit at distances ranging from 800-3200 meters from the source (see Sehmel, 1984 for review). Since the uranine particles were on the order of one micrometer in diameter, this might suggest that anthrax particles with mass median diameter of 2-3 microns will deposit at similar rates.

The deposition velocities experimentally-determined for uranine particles span a range from 0.03 to 30 cm/s. Deposition velocities used in the HPAC 3.0 dispersion model (DSWA and FEMA) for chemical agents are typical for gases. For example, tabun, sarin, and VX are listed as having deposition velocities of 0.3 cm/s, soman and tri-ethyl phosphate 0.5 cm/s, and mustard and GF 1.0 cm/s. This suggests that deposition of these agents over distances of kilometers would be significant.
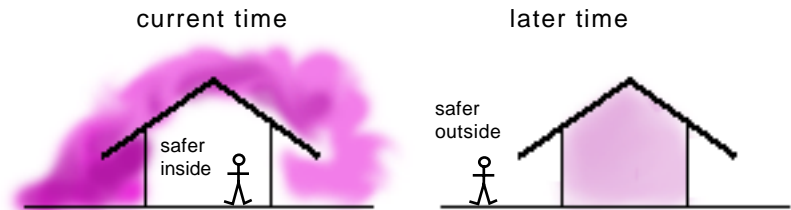
2.10 Indoor Effects

2.10.a) Implications

For an outdoor plume release, closing the windows and doors and staying inside may be initially safer than remaining indoors. Due to infiltration (e.g., leaks, ventilation) and the eventual passage of the bulk of the plume, there may come a time when it is actually safer to be outdoors rather than indoors.

Emergency response decisionmakers responsible for public announcements should be aware that safe zones may change from inside buildings to outside buildings during the course of an event. Simple dispersion models exist to approximate both outdoor and indoor concentrations as a function of time. Unfortunately, the ventilation of buildings is case dependent, so that strict guidelines for when to go outside may be difficult to derive.

2.10.b) Evidence/Documentation

We are not aware of any field or wind-tunnel experiments that have measured the indoor and outdoor concentrations from a short-time plume release. However, a modeling study by Sextro and Daisey (1998) indicates that as an outdoor-released plume passes a building, the concentrations inside are initially smaller due to limited infiltration. At later times, after the plume has passed by the building, the concentrations can be higher inside the building due to limited ventilation.

There have been a number of field studies measuring indoor and outdoor concentrations simultaneously of typical air pollutants (e.g., nitrogen oxides, carbon monoxide, ozone, particulates, volatile organic compounds). Although the sources are typically not representative of short-time plume releases, the results from these studies can be used to help interpret indoor vs. outdoor relationships. Results should be viewed with caution, however, as indoor sources of air pollution (e.g., CO from stoves, VOC's from carpets and paints) can confuse comparisons.

Several studies indicate that pollutant levels indoors follow the general trends outdoors (e.g., Gil et al., 1997; Lee et al., 1997; Desantis et al., 1992). Ekberg (1994) found that indoor concentration variations were smoothed out relative to outdoor variations for buildings with low air change rates. A study by Horvath et al. (1997) in Santiago showed that the peak in indoor particulate measurements lagged outdoor measurements by about 2 hours. A study by Rubino et al. (1998) in an office building found carbon monoxide concentrations following a similar pattern. However, another study by Ando et al. (1996) showed that the peaks in measurements indoors and outdoors correlated well, but showed no time lag. These differences may have resulted from different building ventilation rates.

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